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STRATEGIC BLUE-GREEN OPTICAL COMMUNICATIONS PROGRAM PLAN.

Investment strategy toward an optical solution for satellite-to-submarine information transfer

Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee.

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Arlington VA 22209

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A comprehensive data base in blue-green propagation and devices developed at NOSC and elsewhere was used to evaluate the feasibility of a space-based laser strategic satellite-to-submarine communication system designed to broadcast to operationally significant ocean areas of the world. Although a major capability in submarine communication can be obtained by sequentially transmitting data at a moderate rate to small spots that span the total operational area, this capability can be realized only by the correction of major deficiencies in the current blue-green technology base. Dramatically better optical filters and much more efficient and powerful

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lasers must be developed before the technical risk of the concept is reduced to a satisfactory level. Also required are the resolution of major uncertainties in the transmission of optical energy through clouds and a reduction in the uncertainties associated with present oceanic and cloud climatology data bases.

The overall objective of the program is to determine the practicality and suitability of an optical solution for transmitting strategic information to submerged submarines. This document describes the current program plan. It outlines the various system approaches being pursued, the technical uncertainty areas in both channel characterization and subsystem technology, and the investment strategy to be followed to meet the objective.

CONTENTS

1 INTRODUCTION

The Navy has long recognized that the so-called "blue-green window" for energy transmission through the oceanic channel offers a potentially significant capability for information transfer to submerged submarines at operational speeds and depths. This recognition, in turn, has spurred continuing efforts to develop a comprehensive data base in blue-green propagation and devices at NOSC and elsewhere. Recently, the technology base was used to evaluate the feasibility of a space-based laser strategic satellite-to-submarine communication system designed to broadcast to operationally significant ocean areas of the world.* The results of this study indicated that a major capability in submarine communication can be obtained by sequentially transmitting data at a moderate rate to small spots that span the total operational area. The investigation also made it eminently clear, however, that this capability can be realized only by the correction of major deficiencies in the current blue-green technology base. In particular, dramatically better optical filters and much more efficient and powerful lasers must be developed before the technical risk of the concept is reduced to a satisfactory level. Required in addition are the resolution of major uncertainties in the transmission of optical energy through clouds and a reduction in the uncertainties associated with present oceanic and cloud climatology data bases. If these problems can be solved, as is the intent of the Strategic Blue-Green Optical Communications Program, a highly important communication capability can be realized.

The specific overall objective of the program is to determine the practicality and suitability of an optical solution for transmitting strategic information to submerged submarines. This document describes the current program plan. It outlines the various system approaches being pursued, the technical uncertainty areas in both channel characterization and subsystem technology, and the investment strategy to be followed to meet the objective.

2 TECHNICAL PROGRAM APPROACH

If the program objective is to be met quickly and cost-effectively, an investment strategy must be developed. This requires both a clear understanding of the inherent physical and engineering problems associated with this emerging technology and knowledge of the strategic submarine communications operational requirements. Note that the question to be resolved is one of practicality and suitability rather than of feasibility. The feasibility of limited satellite-to-submarine communications is well established on the basis of system analyses such as reference 1 and well supported by experimental results, such as the SAOCS* and OPSATCOM (ref 2) experiments. Thus there is apparently no fundamental physical impediment to conceptual operation. The unresolved issues are system performance, cost, and risk – factors that take into account all aspects of the problem, such as area coverage, availability, spoofing, and depth, as well as their relationship to the strategic submarine operational requirements. Their quantification and comparison with existing and proposed means of submarine communications will show whether an optical system could augment the current Navy capability, hence will determine the future of this program.

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*Reference available to qualified requestors.

1. Optical Communications Between Underwater and Above Surface (Satellite) Terminals, by S Karp; IEEE Trans on Comm, COM-24, no 1, p 66–81.
2. NOSC Technical Document NELC TD 490, OPSATCOM Field Measurements, vol I and II, by R Driscol, F Martin, and S Karp, 1 June 1976.

The approach taken in developing the investment strategy for the program was as follows:

1. Establish the strategic submarine communication requirements.

2. Define the system concepts that have potentially the highest probability of meeting envisioned operational requirements for strategic communications and of minimizing their vulnerability to threat.

3. Assess channel characterization and subsystem technology to determine which facets have major technical uncertainties that will impede a performance-cost-risk analysis.

4. Define any and all medium-scale demonstrations and experiments that should be performed for either scientific or political reasons.

5. Couple the information in items 1–4 with the yearly funding levels of a total program "cycle," to derive an investment strategy. The program cycle is the program duration for either 6.2, 6.3A, or 6.3, or any combination of these three development cycles – in our case, 6.2.

From this approach, the following key areas naturally emerge to form the major task areas of the problem:

Operational requirements; threat definition and vulnerability analysis

System engineering

Channel characterization

Subsystem technology

System demonstration and experiment

Not surprisingly, these five task areas are synergistic, as the following definitional statements show.

The operational requirements and threat definition task area defines the communications problem at hand. It provides the yardstick with which performance is measured and constrains the variability of system concepts and designs. NOSC, in its role as the program technical advisor, will work (through PME 117) with pertinent OPNAV codes to further refine the list of operational requirements germane to strategic submarine communications.

System engineering represents the central thrust of the program. This task establishes baseline performance levels and represents the vehicle for generating and exercising conceptual alternatives. It also provides information on the sensitivity of "optimum" design(s) to the variability of key channel parameters and subsystem technology – information that is then used by NOSC in concert with the system contractors to generate cost and risk assessments relative to performance uncertainties and strategic operational requirements.

Channel characterization defines the physical impact of the channel (ie the atmosphere, clouds, air-sea interface, and ocean) on the transmission of blue-green energy from the satellite to the submarine. This task has as its objective the determination of the quantity and form of both the optical signal and the noise energy available at depth for detection.

Subsystem technology establishes the components, devices, and subsystems that are or will be available to construct a proposed system. The channel characterization task influences this task, since subsystems such as filters, adaptable receivers, signal processors, etc are governed by the temporal, angular and spatial form of the received energy at depth. The determination of performance levels of components as well as their interrelations to form a subsystem are critical. Subsystem technology, together with channel characterization, drives communication system engineering.

System demonstrations and experiments are practical, scaled-down verifications of the systems concepts that are required both for political and technical reasons. They represent a means to check projected against actual performance at a given level of technology maturity.

A more detailed description of all five task areas is given in section 4.

3 SYSTEM CONCEPTS

Three distinctly different optical communications concepts are recognized as having the highest probability of meeting the envisioned operational requirements for strategic communications: space-based laser communications, earth-based laser communications, and SUNSUBSATCOM. This brief description of the three system approaches highlights some of their basic differences and common elements.

SPACE-BASED LASER COMMUNICATIONS

Figure 1 depicts the basic geometry of a space-based laser satellite-to-submarine communications link. A conventional rf antenna transmits the initial data stream to the satellite, in which the laser transmitter is housed. The laser transmitter then scans its assigned operational area with a small spot (about 10-100 km in diameter), dwelling only long enough at each location to transmit the initial message.

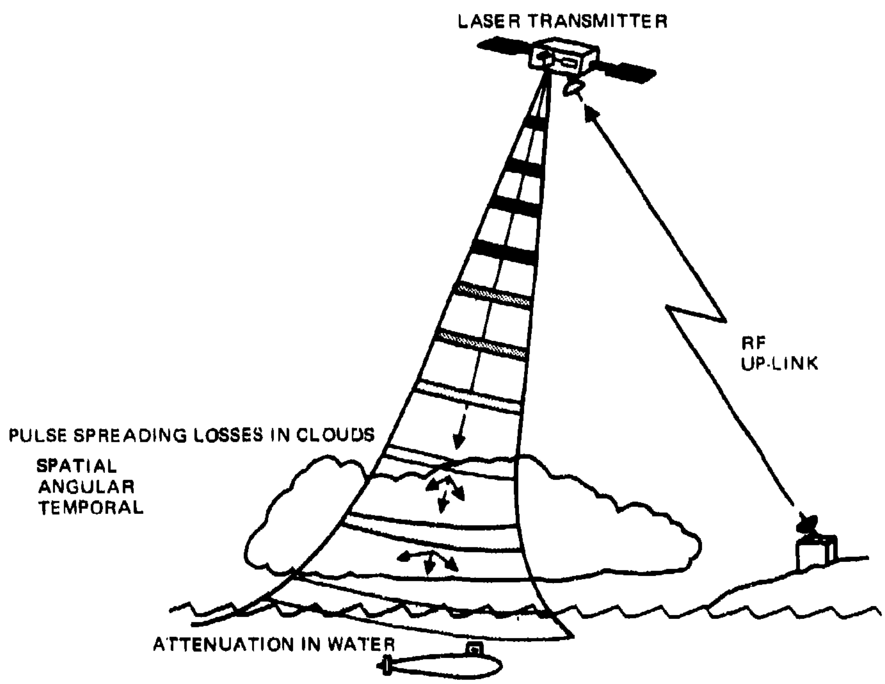

Figure 1. Geometry of the space-based laser satellite-to-submarine communication link.

System analyses performed to date indicate that the required laser power is a strong function of the cloud and water losses. The required energy is relatively independent of the atmospheric propagation path length, thus permitting a certain amount of freedom in the orbital placement within beam entry angle constraints at the air-water interface.

The down-link optical power requirement, which is driven by the interaction of propagation path losses and receiver performance, is one of the most important parameters that affect the cost and complexity of the space-based transmitter concept. The required optical power, together with the electrical-to-optical conversion efficiency of the selected laser, determines the power required and thus the weight and mass of the satellite. The mass of the satellite affects the cost of its placement in a given orbit.

Satellite placement cost not only is incurred to achieve the initial operational capability but recurs as a function of expected satellite transmitter lifetime. Present laser technology is limited by the reliability and lifetime of the pumping source or mechanism involved. Fortunately, work currently is being funded by the Naval Electronic Systems Command to alleviate these problems. The results of that work will largely determine whether or not this system approach will be recommended for future 6.3 development and beyond.

HIGH-ENERGY EARTH-BASED LASER

The earth-based laser concept employs an optical up-link from one or more high-energy laser transmitters to one or more orbiting mirrors. The final reflecting satellite then directs the beam to the surface to service the appropriate operational area. This concept is shown in figure 2.

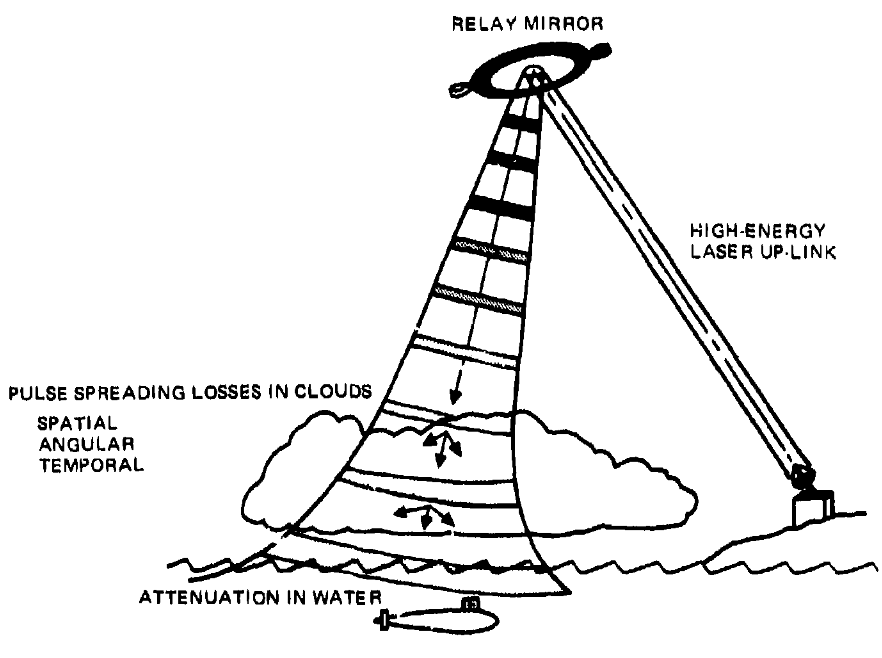

Figure 2. Typical geometry of a single-element relay down-link Earth-based laser communication system.

Although the system constraints are quite different for the earth-based laser concept in which orbiting relay mirrors are used, many of the down-link channel characteristics are the same as for the space-based laser approach. The accessibility of the laser is the primary advantage of this approach. It significantly relieves the lifetime problems while promising much higher average transmitter power. However, initial power levels are approximately an order of magnitude larger than required in the space-based approach. Also it is difficult to find locations for laser transmitters under cloud-free skies, preferably at high altitudes, at which large quantities of electrical power can be provided. Furthermore, the earth-based transmitter concept requires the development of real-time, large-diameter adaptive optics. Adaptive optics are used to compensate for atmospheric distortions of the up-link optical beam, which limit the minimum transmitter divergence. This compensation is further complicated by the possibilities of "blooming" and other nonlinear effects induced by the high optical power densities required by this approach, affecting both the quality and control of the up-link beam at altitude.

SUNSUBSATCOM

An optical satellite-to-submarine communication concept using a large orbiting collector or mirror to direct modulated solar radiation to the submerged receiver has also been suggested. In this scheme, a conventional rf transmitter sends the initial message to the satellite. The satellite then codes this message onto direct sunlight and directs the beam to its operational area assignment as in both previous concepts, ie sequentially scanning the assigned OPS area with small spots.

This approach would remove the requirement for high-energy lasers and narrow-bandwidth optical filters. Collectors with diameters on the order of 60–100 metres would be required for reasonable performance.

The principal risk areas for this approach are (1) the assembly and alignment of such large mirror arrays and (2) pointing and modulation limitations of the output optical signal.

4 DETAILED DESCRIPTION OF TASK AREAS

OPERATIONAL REQUIREMENTS; THREAT DEFINITION AND VULNERABILITY ANALYSIS

The operational requirements exist as the independent variables in any system equation and act as the forcing function to the system engineering process. The formulation and statement of the operational requirements are prerogatives of the end user of the potential system or of the program sponsor acting for the end user. Any of the system engineers must be prepared to advise NOSC on the consistency, utility, and completeness of those requirements to the extent that the system engineering process opens new issues and techniques outside the previous experience of the end user. It is the responsibility of the program technical advisor to act on such advice and to suggest modifications of those requirements, if warranted, to the sponsors.

A closely related task area involves threat definition and system vulnerability. This task area interfaces the strategic and operational impact of a system design to our program objective. Threat definition and system vulnerability analyses require access to very specialized data bases because of their interpretive nature, and this task area should be addressed as a separate issue, exclusive of any system approach or concept. On a continuing basis, NOSC, as technical advisor to the program, will collect the results generated by this task and distribute them to the appropriate system engineering contractors.

SYSTEM ENGINEERING

To meet the overall objective of this program, each of the contractors associated with a particular system approach will produce the performance, cost, and risk information necessary to make the system approach comparison. To effectively bound the problem of comparing the various system concepts, each contractor on submitting his study results to NOSC will highlight the system designs that appear optimum in meeting all strategic operational requirements. To further facilitate the approach comparison, each of the system contractors will assess his designs in terms of three comparison parameters: subsystem risk, system risk, and cost.

The subsystem risk parameter is defined as the product of three parameters: the "state of technology" parameter, the "signal-to-noise impact" parameter and the "system impact" parameter, all evaluated on a 1–5 scale. Because each system is composed of various subsystem components, the subsystem risk parameter is a weighted sum of the product of the above factors for each component. That is,

$$\text{subsystem risk parameter} = \frac{\sum_{j=1}^{N} W_j \times A_j \times B_j \times C_j}{\sum_{j=1}^{N} W_j},$$

where

W = weighting factor for each subsystem

A = state-of-technology parameter

B = signal-to-noise impact parameter

C = system impact parameter

N = total number of subsystem components

The discussion under Subsystem Technology, later in this section, implements the above method in more quantitative terms, setting all the weighting factors to 1.

The overall "system risk" parameter is the factor that takes into account that the overall system risk is more than merely the sum of the individual subsystem risk parameters. It includes such system issues as environmental impact effects, threat and vulnerability, broadcast format and throughput flexibility, total system complexity, etc.

The "cost" parameter obviously relates to the total system cost. This allows us to define a "system comparison" parameter, given by the following product:

$$\begin{matrix}\text{system comparison} \\ \text{parameter}\end{matrix} = \begin{matrix}\text{subsystem risk} \\ \text{parameter}\end{matrix} \times \begin{matrix}\text{system risk} \\ \text{parameter}\end{matrix} \times \begin{matrix}\text{cost} \\ \text{parameter}\end{matrix}$$

To obtain this number, the following methodology will be employed:

a. Define strategic submarine operational requirements. An initial set of requirements is available and will be continually refined and updated by NOSC, the program technical advisor.

b. Develop a transmission channel model. An initial Navy blue-green down-link channel is currently available as an NOSC technical report (ref 3). Although this model has yet to be totally verified, it will be verified and updated as the program progresses. All system contractors will be required to use this model to guarantee consistency of propagation calculations.

c. Define component technology status. This will be performed in concert with NOSC, the program technical advisor.

d. Define one or more optimum optical communication system configurations. In particular, each system contractor will provide information including but not limited to the following:

(1) Optical transmitter specifications (eg output power, pulse rate, input power requirements, anticipated lifetime, maintenance requirements) and their associated costs and risks.

(2) Optical receiver specifications (eg aperture size, FOV, type and bandwidth of envisioned spectral filter, detection electronics) and their associated costs and risks.

(3) Coding and decoding processing electronics and the costs and risks thereof.

(4) Life-cycle costs of the entire system.

(5) Satellite configuration (eg number of satellites, sizes, the weight, number, and type of solar panels used, other energy sources on board and the heat dissipation mechanisms and efficiencies thereof).

(6) Cost of deploying the entire system (eg installation of receiver on submarine, satellite launch).

(7) Network and injection link design and the associated costs and risks thereof.

(8) Pointing and tracking design (eg mirror requirements, adaptive capability, resolutions, gimbal type, control electronics) and the associated costs and risks thereof.

(9) Sensitivity of the entire system to atmospheric and oceanic conditions in terms of cost and risk.

(10) Schedule and cost to achieve initial operational capability (IOC).

e. Minimize the above system design(s) in terms of cost and risk while simultaneously maximizing performance.

f. Document the above system design in a link budget.

g. Deliver all results to NOSC for inclusion in a system approach comparison and sensitivity analysis.

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3. NOSC TR 387, Naval Blue-Green Single-Pulse Downlink Propagation Model, by Technical Advisor to the Blue-Green Optical Communications Joint Coordinating Committee, 1 January 1979.

Figure 3 is a graphic representation of the above task procedure. By follow' this method, a realistic system assessment of the earth-based, space-based, and SUNSUL · TCOM approaches, in terms of performance, cost, and risk, can be produced quickly and cost-effectively.

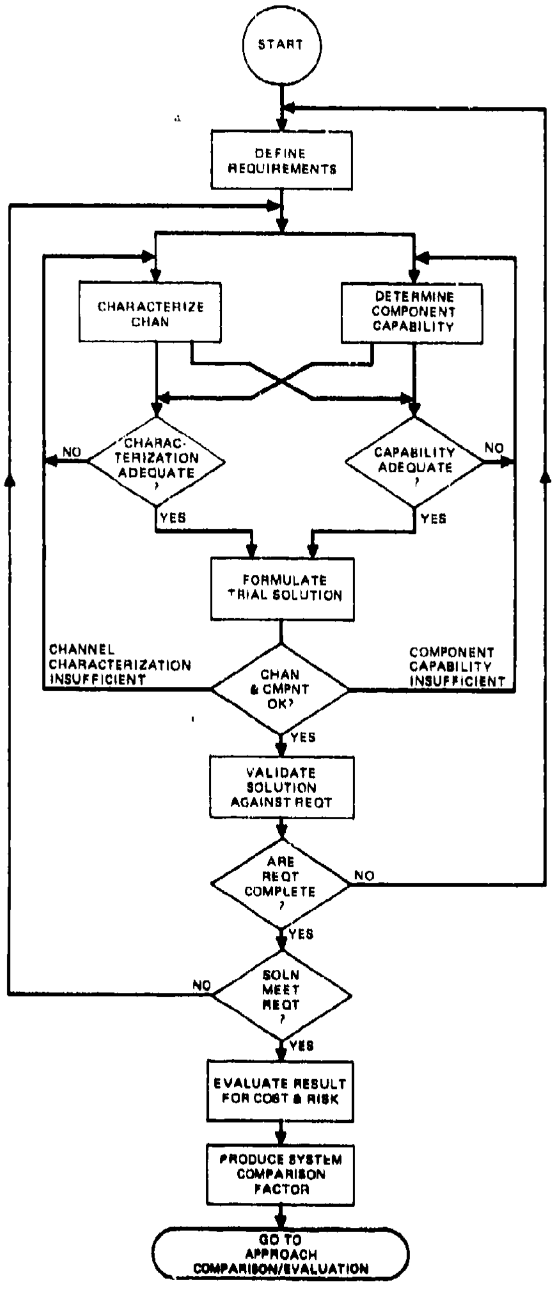

Figure 3. System engineering flowchart.

CHANNEL CHARACTERIZATION

In the approach to satisfy the program objective, it is implicit that an accurate assessment of the performance of a strategic submarine optical communication system rests, for the most part, on an accurate model of the transmission channel. The transmission channel "scales the magnitude of the problem": the effects of the channel on the initial radiance distribution (appendix A) affect both the system component specifications (and hence component projected performance) and the magnitude and form of the signal available for detection, given the optimal (channel-derived) system design (ref 1). The importance of this fact cannot be overstated; the channel defines both the amount of signal available and the nature of the components required to extract that signal from the noise. Hence, although the central thrust of the program is communication systems engineering, a major portion of our initial effort is to resolve channel uncertainties that greatly affect system performance and system design.

The first question is one of priorities: how does one decide which area of channel uncertainty do and do not need immediate or near-term resolution, in light of the need for a quasi-optimum system design within the near future? The answer is found by the following six-step approach.

a. Develop a modular analytical model for the total transmission channel.

b. Assess the technical uncertainty of each individual submodel of the total channel model.

c. Assign each submodel a knowledge factor, A, a signal availability factor, B, and a system design factor, C. These factors are defined in the next paragraph.

d. Compute the determination factor, D, for each submodel.

e. If $D \gg D_0$, where D_0 is a preassigned threshold, upgrade the submodel and return to step b. If $D \ll D_0$, go to next step. If $D \approx D_0$, reevaluate the submodel; either go to next step or upgrade the submodel and go to step b.

f. Place in "final" channel model.

Figure 4 is a graphic representation of the above approach.

The modular channel model developed by NOSC and GTE Sylvania (ref 3) was based on the best available theories, estimates, and data bases. The technical uncertainty of each individual submodel of the total channel model is assessed in terms of its knowledge uncertainty, signal availability impact, and system design impact. Table 1 gives the criteria on which quantization of these uncertainties and impacts was based. The knowledge uncertainty factor, A, is a quantitative (numerical) assessment of the level of technical uncertainty of the particular channel submodel. The signal availability impact factor, B, is a numerical assessment of the impact of the submodel uncertainty on the amount of available signal energy. The system design impact factor, C, is a numerical assessment of the impact of the submodel on the total system design. Table 2 shows a compilation of the quantified technical uncertainties for the 23 submodels.

Using these factors, we compute a determination necessity factor, D, for each submodel as follows:

$$D = A \times B \times C .$$

Column D of table 2 gives the determination necessity factors thus computed from columns A, B, and C.

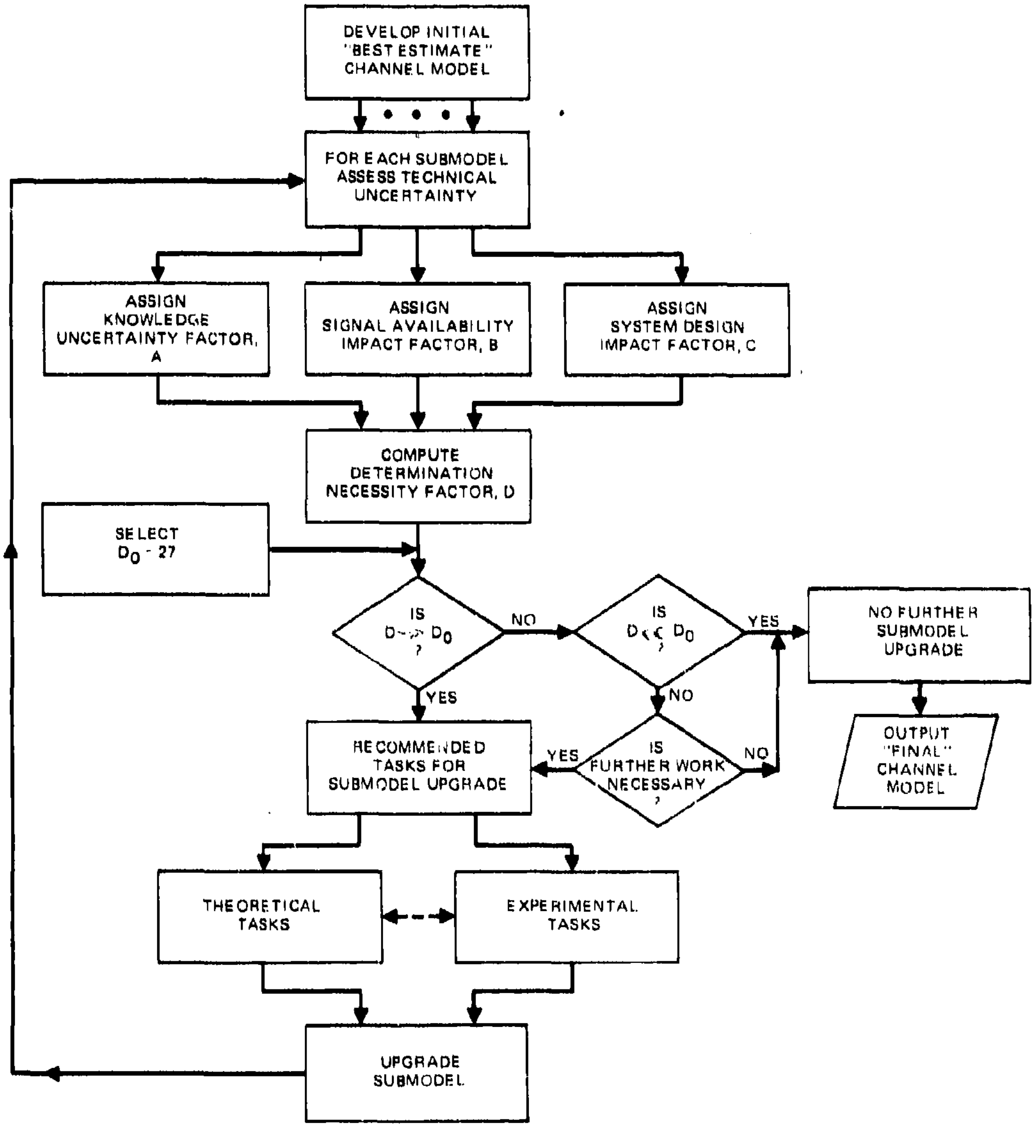

Figure 4. Channel characterization model upgrade flowchart.

Table 1. Quantization criteria for submodel uncertainty and impact factors.

A – KNOWLEDGE UNCERTAINTY FACTOR

1 – Well understood, both theoretically and experimentally (little controversy)

2 – Well understood theoretically but little, if any, experimental verification

3 – Moderate understanding both theoretically and experimentally (moderate controversy)

4 – Moderate understanding theoretically but little experimentally

5 – Not well understood either theoretically or experimentally

B – SIGNAL AVAILABILITY IMPACT FACTOR

1 – Negligible impact on signal energy availability

2 – Small impact on signal availability

3 – Medium impact on signal availability

4 – Large impact on signal availability

5 – Major impact on signal availability

C – SYSTEM DESIGN IMPACT FACTOR

1 – Negligible impact on system design

2 – Small impact on system design

3 – Medium impact on system design

4 – Large impact on system design

5 – Major impact on system design

The determination necessity factor, when compared to some predetermined threshold value, indicates whether or not this submodel should be upgraded immediately to ensure a quasi-optimum system design and therefore a quasi-accurate prediction of performance. We have arbitrarily set our threshold value at 27 ($3 \times 3 \times 3$). Thus for $D \ll 27$, we need not recommend submodel uncertainty resolution within the near future. For $D \gg 27$, we recommend that work in this area be performed. For $D \approx 27$, we look at the particular submodel in more detail and make a decision on whether or not to recommend work. This is the ever-present "gray area."

On the basis of table 2, the following submodels should be upgraded in the order indicated:

1. Atmospheric climatology data base; oceanographic (underwater propagation) data base
2. Thick clouds
   - Transmittance
   - Multipath time spread
3. Air-sea interface
   - Source coupling
   - Effects of wave action and sea foam
   - Radiance redistribution

Table 2. Evaluation of channel characterization.

Submodel	A Knowledge Uncertainty Factor	B Signal Availability Impact Factor	C System Design Impact Factor	D Determina-ation Necessity Factor	Tasks Funded to Address Issue
Clear atmosphere transmission	1	2	2	4	√
Thick clouds					
Cloud transmittance	2	5	5	50	√
Zenith angle dependence	2	3	2	12	
Multipath time spread	3	5	5	75	√
Radiance distribution	2	2	3	12	
Single scatter albedo	4	2	2	16	
Thin clouds					
Cloud transmittance	3	3	3	27	√
Zenith angle dependence	1	1	1	1	
Multipath time spread	3	2	3	27	√
Radiance distribution	4	2	2	24	√
Single scatter albedo	4	1	1	4	
Atmosphere climatology data base	5	5	5	125	√
Cloud-to-water transmittance	2	2	2	6	
Air-sea interface					
Source coupling through interface	5	3	3	45	√
Effects of wave action and sea-foam	4	3	3	36	√
Radiance after traversed	3	3	3	27	√
Underwater propagation					
Resulting radiance distribution for					
collimated surface illumination	3	4	3	36	√
diffuse surface illumination	3	3	3	27	√
Multipath time spread	2	2	2	8	
Oceanographic data base	5	5	5	125	√
Received pulsewidth and shape	2	2	4	16	
Background noise sources					
Nonclassical noise (eg bioluminescence)	5	1	5	25	
Blue sky	3	1	4	12	

4. Thin clouds

   Transmittance
   Multipath time spread

5. Underwater propagation – resulting radiance distribution

   Collimated surface illumination
   Diffuse surface illumination

These tasks have been or are being funded (see section 6). Additional tasks in channel characterization for FY 80 and FY 81 based on this analytical technique are described briefly in section 5.

SUBSYSTEM TECHNOLOGY

The performance of optical down-links for strategic communications from satellites to submerged submarines is being thoroughly examined by means of system link models. Such communication channels have been shown to be limited severely by the state of the associated component technologies. Components now available are inadequate to provide even a reduced initial capability. An order-of-magnitude advance in component technology is absolutely essential before any of the strategic blue-green concepts are moved into advanced development.

Neither low- nor medium-risk technology-based systems meet the requirements or reasonable variations thereof. Major advances are required in the power, lifetime, and efficiency of lasers and in receiver aperture and optical bandwidth. (An introductory review of blue-green laser technology is included as appendix B.) Optical receiver improvements in design, filters, detectors, and detection criteria are needed. (An introductory review of blue-green optical filter technology is included as appendix C.) Adaptive communications formats to allow for channel degradation need to be investigated. In addition, component technologies should be pursued near the optimum channel wavelength of 475 nm. There do not appear to be any fundamental physical roadblocks to such advances; for the most part, specific development approaches are envisioned.

Fortunately, order-of-magnitude improvements appear to be achievable in many of the key component technologies on which link performance critically depends. But in some of the other technologies it is not clear how advancements will be realized or precisely what approach will be successful in achieving the necessary gains.

Table 3 defines the terminology and criteria used in qualitatively evaluating the state of the individual technologies, the impact on receiver signal-to-noise ratio, and the impact on system design based on assessments of risk, complexity, size, and reliability. In table 4, the key components whose performance levels are critical to the realization of blue-green strategic optical communications down-links are evaluated qualitatively by means of these criteria, for each of the three system concepts.

While the ratings assigned in table 4 are subjective and may be evaluated differently by others, they serve nevertheless to order the criticality of subsystem technologies that require programmatic emphasis. Depending on budgetary constraints and new technological ideas to be exploited, this table can serve as a guide for funded work, with subjects scoring above some threshold value (say 48) being candidates.

A further interesting output of the ratings in table 4 is obtained by summing the products of the risk factors by system concept. This provides an indicator of overall system difficulty for the three system concepts.

Table 3. Quantization criteria for evaluating the state of critical component technologies.

STATE OF TECHNOLOGY

1 – Well understood both theoretically and experimentally

2 – Well understood theoretically; some hardware exists

3 – Theoretical concepts proposed and accepted

4 – Several theoretical approaches; no selected approach

5 – No theoretical approach identified to satisfy need

SIGNAL-TO-NOISE RATIO IMPACT

1 – Negligible impact

2 – Small impact

3 – Medium impact

4 – Large impact

5 – Major impact

SYSTEM IMPACT

1 – Negligible impact

2 – Small impact

3 – Moderate impact that may affect design approach

4 – Major impact

5 – Major impact; feasibility at issue

SYSTEM DEMONSTRATIONS AND EXPERIMENTS

The system demonstrations and experiments task is intended to verify the concept of optical strategic communications with submarines. To accomplish this objective, the scope of the demonstrations and experiments must be defined and an appropriate experimental plan must be developed.

The first such demonstration should be of the down-link, by which information is sent through clouds and water, during daytime, to operationally significant depths. Since this link is identically common to two of the three system concepts and has areas of relevance to the third, planning and definition tasks can be started before the system concept comparison and selection are performed.

After one system concept is selected, there will be need to conduct other demonstrations and experiments to address concept-peculiar issues – transmitter-spacecraft integration, up-link adaptive optics and tracking, etc.

Table 4. Evaluation of key components for each of the three system concepts.

Technology Area	System Concept*	A State of Technology	B Signal-to-Noise Impact	C System Impact	D* Product A × B × C I	II	III
Laser	I	5	5	5	125		
	II	4	5	5		100	
	III	N/A	N/A	N/A			–
Optical filter	I, II	3	5	4	60	60	
	III	1	2	2			4
Optical detectors	I, II	2	3	3	18	18	
	III	1	3	3			9
Adaptive optics	II	3	5	5		75	
Open-loop pointing	I	3	5	5	75		
	II, III	4	5	5		100	100
Space structures	I	1	4	4	16		
	II	3	4	4		48	
	III	4	4	5			80
Receiver Engineering	I, II	4	4	4	64	64	
	III	2	5	3			30
Antifouling optics	I, II, III	4	4	3	48	48	48
Satellite systems	I	3	4	3	36		
	II	4	5	4		80	
	III	4	5	5			100
	Overall system difficulty for the three system concepts →				442	593	371

*I – Spaced-based laser concept
II – Earth-based laser concept
III – SUNSUBSATCOM

5 CURRENT FY 79 PROGRAM

The following abstracts briefly describe the various tasks of the current FY 79 program as funded.

SYSTEM ENGINEERING TASKS

Space-based Laser System Engineering

Complete an orbiting laser transmitter system model that includes a computer down-link model, up-link and down-link architecture, loss budgets, and system configuration trade-offs.

Earth-based Laser System Engineering

Develop an earth-based laser transmitter system model that includes adaptive optics, point-ahead tracking algorithms, orbiting mirror relay systems, link budgets, and system configuration trade-offs.

Program Technical Advisory Task

Coordinate the Strategic Blue-Green Optical Communications Program. Provide overall systems engineering in establishing and defining methods of approach, evaluating proposed tasks against operational requirements, performing system approach trade-offs, and evaluating the results of those trade-offs; assist sponsors in reviewing work in progress and determining new tasks required to close the system engineering loop in order to converge on a practical and deployable system design; maintain and update the blue-green communication system channel model as a key system engineering tool.

CHANNEL CHARACTERIZATION TASKS

Multi-Light-Level Teleradiometer

Build, deliver, install, and check out a teleradiometry instrumentation package that can measure cloud transmission and infer mean propagation length by means of the differential oxygen absorption of solar and lunar sources. Measurements simultaneous with cloud propagation experiments are intended to validate the inferability of multipath time spread and its statistical deviation.

Diffusion Regime Cloud Propagation

Perform a down-link cloud propagation experiment to measure the attenuation and pulse stretching of a pulse signal as a function of meteorological parameters. This experiment is intended to extend the measurement data base to the diffusion propagation regime.

Make measurements simultaneously with differential teleradiometry measurements, for validation and calibration. Compare output data with propagation models to develop updates and improvements to the system channel model. It is assumed that NOSC will provide meteorological support for this experiment.

Multiply Forward-Scattered and Knollenberg Cloud Propagation

Continue work to determine experimentally the performance of a land-based blue-green surface propagation channel through marine fogs. Compare experimentally gathered data on regions of direct propagation and multiply forward-scattered propagation with the various theoretically and statistically derived models. Assess the uncertainty of Knollenberg optical thickness determination by comparison of this quantity with integrated optical thickness measurements. This establishes the uncertainty associated with diffusion regime cloud propagation measurements.

Cloud Propagation Modeling

Analytically characterize the interaction of a pulse plane wave through clouds and at the air-sea interface. Compare resultant characterizations with results of propagation experiments for validations, as inputs and updates to the blue-green communication system channel model.

Laser Communication Climatology Study

Assemble a cloud occurrence and classification data base from the Air Force three-dimensional nephelometry (3D NEPH) data base, with a goal of a global descriptive cloud occurrence data base. Combined with cloud propagation data and teleradiometry measurements, the results of this task will permit an adaptive exploitation of channel characteristics by giving an "other than worst case" dimension to the cloud propagation portion of the system channel model.

Assessment and Modeling of Ocean Optical Properties

Develop an oceanographic data base from the Nimbus-G satellite data, with the goal of inferring the diffuse attenuation coefficient, k, from these data. Develop and apply appropriate techniques of optical oceanography and bathimetry to gather "truth data" with which to validate the satellite-derived data base and to determine the extendability of that data base beyond the near-surface region. The output of this task, a general ocean model for blue-green propagation, is to serve as a major input to the system channel model.

SUBSYSTEM TECHNOLOGY TASKS

Satellite Laser

Ensure that laser requirements are being addressed in laser development programs at the present time and that no laser component development is being funded directly by the Strategic Blue-Green Optical Communications Program. Exploratory development (6.2) of blue-green laser technology is being pursued by the Navy under "Electro-Optic Device Technology" program element 62762(N), work element XF62583091. This work is managed by the Electronic Technology Division of the Naval Electronic Systems Command (NAVELEX 304) and is directed by the program manager at NOSC. To ensure coordination with the blue-green strategic communications requirements, the NOSC Strategic Blue-Green Optical Communications Program manager is also the manager of the electro-optical device technology exploratory development program. Additionally, a research program (6.1) in blue-green device technology (lasers and filters) is sponsored by the Office of Naval Research (ONR). A close relationship between both the 6.2 and 6.1 efforts is achieved by involving all the principals in the planning and coordinating phases of both programs. At present the following objectives have been established for the satellite-based laser:

Energy per pulse	0.5–5 J
Wavelength	430–530 nm
Pulse rate	25–100 pulses per second
Overall efficiency	> 1%
Lifetime (at 50% duty cycle)	10^8–10^{10} shots

Earth-based Laser

Observe, predict, and maintain knowledge of progress in blue-green high-energy laser technology. Development of the earth-based laser is an expected output of the high-energy visible laser program of the Defense Advanced Projects Research Agency, Strategic Technology Office (DARPA STO). Requirements for the earth-based laser are still in the process of being defined. The following is a partial set:

Pulse energy	4 kJ
Pulse width	1 μs max
Pulse rate	100 pulses per second max
Wavelength	460–510 nm

Lyot Filters

Explore the practicality of the Lyot filter by constructing proof-of-concept test specimens. This filter technology is the most promising near-term filter improvement. The exploratory program will develop narrow-passband, large-aperture plastic filters and will build prototype filters for testing and evaluation that are optimized for use at 500 nm. The goals for the prototype filters are 300 mm diameter, 0.1 nm passband of 25% unpolarized light transmission, and ±30° field of view.

Atomic Resonance Filters

Investigate the radiative transport phenomenology of possible atomic resonance filter mechanisms, and characterize the pulse response of a realizable filter as a function of upper-state lifetimes and possible buffer gas pressure broadening effects. Present problems include the following:

- A limited number of fixed lines provided principally by the use of alkali metal vapors
- Radiation trapping and long lifetimes in the processes
- Bandwiths which may be too narrow to accommodate Doppler shifts or to control a tunable laser

Isoindex Coupled-Wave Electro-optical Filter*

A new filter concept has recently emerged that is based on the accidental isotropy in the refractive index of certain uniaxial semiconductors that occurs near the band edge. Coupling of light energy between ordinary and extraordinary polarizations can be induced at the isotropic point by an applied dc electric field. When placed between crossed polarizers, these materials can thus act as narrow-band filters. The field-of-view characteristics have been analyzed, and it has been concluded that this type of filter can, in principle, accommodate a field with a bandwidth of less than 0.05 nm. Furthermore, a readily available blue-green filter material has been identified, and a method for tuning the filter across the entire blue-green region has been conceived and is being analyzed theoretically. This task is intended to produce an experimental version of the isoindex filter and to characterize its performance, in light of its perspective role in the Strategic Blue-Green Optical Communications Program. (This task may be part of the NAVELEX 304 blue-green device development effort and should be considered in that light.)

6 INVESTMENT STRATEGY FOR FY 80 AND FY 81

FY 80 PROGRAM

Communications Engineering

To meet the overall objective of this program, each system engineer associated with a particular system approach shall produce the performance, cost, and risk information necessary to make the systems approach comparison. The approach required to meet this goal is outlined in section 4 under System Engineering. The selected approaches are as follows:

- Earth-based laser
- Space-based laser
- SUNSUBSATCOM

*FY79 research in this area is being pursued through Naval Electronic Systems Command (NAVELEX 304) block funding at NOSC.

Oceanographic Data Base and Model

Continue the oceanographic data base and model development being performed by the Scripps Institution of Oceanography. For generation of the data base and model, Nimbus-G satellite remote sensing data are being used. Tasks for FY 80 should include the following:

a. Continued production of the diffuse attenuation coefficient data base.

b. Continued truth verification of the remote sensing technique and uncertainty assessment.

c. Investigation in more detail of the relationship of "surface" and "deep" diffuse attenuation coefficients.

d. Development of an absorption coefficient data base.

e. Continued development of the global computer model.

Atmospheric Data Base Development

Based on initial work by McDonnell-Douglas to develop a cloud climatology global model, fund a program to produce a cloud climatology data base in terms of the optical and physical thickness statistics and the area coverage statistics.

Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee

Continue coordinating the technical portion of the Strategic Blue-Green Optical Communications Program. Provide overall systems engineering in establishing and defining methods of approach, evaluating proposed tasks against operational requirements, performing system approach trade-offs, and evaluating the results of those trade-offs; assist sponsors in reviewing work in progress and determining new tasks required to close the system engineering loop in order to converge on a practical and deployable system design; maintain and update the Navy blue-green down-link propagation model.

HSS Teleradiometer Field Deployment

Provide the necessary comparison data for the verification of the Navy propagation model and cloud climatology data base. In particular, simplified versions of the FY 79-developed HSS teleradiometer will be deployed to various representative locations in the Atlantic and Pacific ocean areas to produce cloud transmission and multipath time spread measurement. These results can then be used as ground truth verification of the Navy down-link propagation and cloud climatology data base models currently under development.

Lyot Filter

Continue the development of the Lyot filter at Lockheed Palo Alto Research Laboratory. This filter technology is one of the two most promising near-term filter improvements. This program includes developing narrow-passband, large-aperture plastic filters and building prototype filters for testing and evaluation. The filters are to be optimized for use at 500 nm. The goals for the prototype filters are 300 mm diameter, 0.1 nm passband of 25% unpolarized light transmission, and ±30° field of view.

Isoindex Coupled-Wave Electro-optical Filter

Continue work begun in FY 79 to include laboratory versions of designed filter.

PSR Model Verification and Data Analysis

Current multiple scattering research by Pacific Sierra Research (PSR) Corporation is intended to result in (1) a computer model that provides the radiance distribution at the exit of a cloud as a function of the physical parameters of the cloud and the characterization of the incident beam and (2) an analytic expression for the width of the received pulse as a function of the above inputs and the receiver parameters. The purpose of the proposed task is to validate the PSR cloud model by comparison with experimental results as provided by NOSC and others. (This was not provided for in the FY 79 contract.)

Angle of Incidence Dependence of the Underwater Radiance Distribution

There is a 5–8 dB propagation-model uncertainty between collimated and diffuse surface illumination for the received power level at depth, based on experimental evidence. This uncertainty appears to be traceable to the various interpretations of the diffuse attenuation coefficient and its definition. However, Scripps Institution of Oceanography has indicated that most ocean water produces no incidence angle dependence (for either signal or noise) of the measured power at depth (>2–4 scattering thicknesses). Recent theoretical and Monte Carlo analyses have suggested a requirement for resolution of these discrepancies. The intent of this task is to resolve this channel uncertainty issue by using either field or laboratory experimentation.

Nonclassical Noise

The intent of this task is to quantify the effects that pertain to nonclassical noise generation in optical communication systems. These include temporal variations in solar background from such effects as atmospheric turbulence, ocean wave motion, dynamic intermittent cloud cover, and the effects of bioluminescence. The approach will be both theoretical and experimental in nature. Prospective subtasks should include the following:

LABORATORY AND FIELD STUDIES OF THE CHARACTERISTICS OF BIOLUMINESCENT ORGANISMS. These studies would be limited primarily to characteristics that might provide interfering background signals for the in-water detector of an optical communication system. The characteristics of particular concern are the specifics of the spectral radiometric intensity distribution (ie $I(\lambda)$ from, say, $\lambda = 450$ nm to $\lambda = 500$ nm) and the time history of the output (ie $I(t)$) of organisms found in the operating areas at 50–150 metre depths. The effect of the degree of kinetic excitation on these characteristics and of the extent to which self-stimulation and photic stimulation exist are also matters of concern that would be addressed.

OPTICAL SCINTILLATION OF BACKGROUND LIGHT BY WAVE ACTION AND DYNAMIC CLOUD COVER.

Threat and Vulnerability Assessment

Continue the system analysis being performed by SRI in assessing the threat and vulnerability of a blue-green satellite-to-submarine communications link.

Blue-Green Laser Communications/ODACS Synergism

There appears to be an overlap between the objective of blue-green laser communications and several other electro-optical programs such as ODACS (Oceanographic Detection and Categorization System) and one or more programs concerned with passive imaging of underwater targets. The potential areas of mutual interest and interaction include technology (laser, detectors, etc), operational objectives, and field test experiments. As a specific example, the ODACS field tests will include experiments that will allow inference of the "beam-spread function" – the irradiance distribution at depth from a pencil beam impinging on the surface. Since equivalency exists between the beam-spread function and the point-spread function, the same equipment could be used to infer the angular distribution of the radiation at depth, a quantity that is very useful for determining the optimum field of view (for daytime operation) for an upward-looking receiver.

The intent of this task is to perform an analysis of the potential interactability of all these programs and to suggest recommended joint tasks.

Underwater Receiver Development

The intent of this task is to develop and test subsystem components, technology, and system approaches to the underwater receiver. The results of both the system engineering and channel characterization tasks will be used to help design optimum subsystem components for use in a blue-green communication receiver. An optimum underwater communication receiver will be designed and fabricated with state-of-the-art components. It is envisioned that the design will take into account (1) system and operational constraints imposed by the submarine, (2) angular FOV optimization related to the presence of intermittent atmospheric clouds, (3) the potential payoff of pointing the receiver to the source with an optimum FOV when the sun and the laser transmitter are not colinear, and (4) adapting the receiver characteristics to depth.

Pointing and Tracking Experiments

The intent of this task is to perform laboratory experiments relevant to the satellite laser pointing and tracking requirements generated in system engineering tasks (see section 5). Subtasks should include the following:

- Implementation of a zoom telescope scanner
- Open-loop capability analysis
- Spot resolution uncertainty evaluation and overlap design

Satellite stabilization requirements

Adaptive scanning considerations

Concept Verification Definition and Test Plan Development

This task involves the concept verification of the system engineering portion of this program. Germane experiments and demonstrations must be performed to help verify the practicality and suitability of blue-green submarine communication. This task should begin near the conclusion of the system engineering tasks (section 5) and concern itself, at least initially, with defining the experiments and demonstrations and developing a comprehensive test plan. Although somewhat vague and unformed at this point, concept verification tasks will become more apparent as more is known about system performance levels, and such tasks probably will move toward a complete demonstration of the capability to communicate data through clouds and water in a quasi-satellite-to-submarine scenario during daylight atmospheric conditions. Coupled with the theoretical system assessment, this demonstration will allow the practicality and suitability of an optical solution to strategic submarine communications to be determined with some degree of confidence.

FY 81 PROGRAM

Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee

Continue the technical coordination of the Strategic Blue-Green Optical Communications Program.

Isoindex Coupled-Wave Electro-optical Filter

Continue the work begun in FY 80 toward development of a large-aperture 30°-FOV optical filter having a bandwidth less than 0.05 nm.

Oceanographic Data Base and Model

Complete development of the global oceanographic data base and data reduction of the pertinent Nimbus-G data at Scripps.

Concept Verification Experiments and Demonstrations

Based on the results of the concept verification definition and test plan development task derived during FY 80, perform relevant experiments and demonstrations supporting the determination of the practicality and suitability of optical satellite-to-submarine communications.

Additional System and Subsystem Technology Tasks

The intent of these tasks is to improve system and subsystem aspects necessary to provide an optical solution to satellite-to-submarine communications.

Underwater Receiver Evaluation

The underwater receiver developed during FY 80 will be tested and evaluated in a laboratory simulation to determine its inherent operating characteristics. The simulation, which will emphasize the detection of small signals in the presence of noise, will (1) determine the effect of nonclassical noise on the system bit error rate (BER), (2) measure the BER under time-varying input conditions that simulate normal propagation occurrences, and (3) evaluate the performance levels of the various subsystem components as well as the signal processing electronics of the system.

Nonclassical Noise

Continue FY 80 task(s) toward the quantification of all nonclassical noise sources.

STRATEGIC BLUE-GREEN OPTICAL COMMUNICATIONS PROGRAM SCHEDULES

Figures 5–7 show the FY 78 to FY 82 Strategic Blue-Green Optical Communications Program schedules for channel characterization, system engineering, operational requirements, subsystem technology, and system demonstrations.

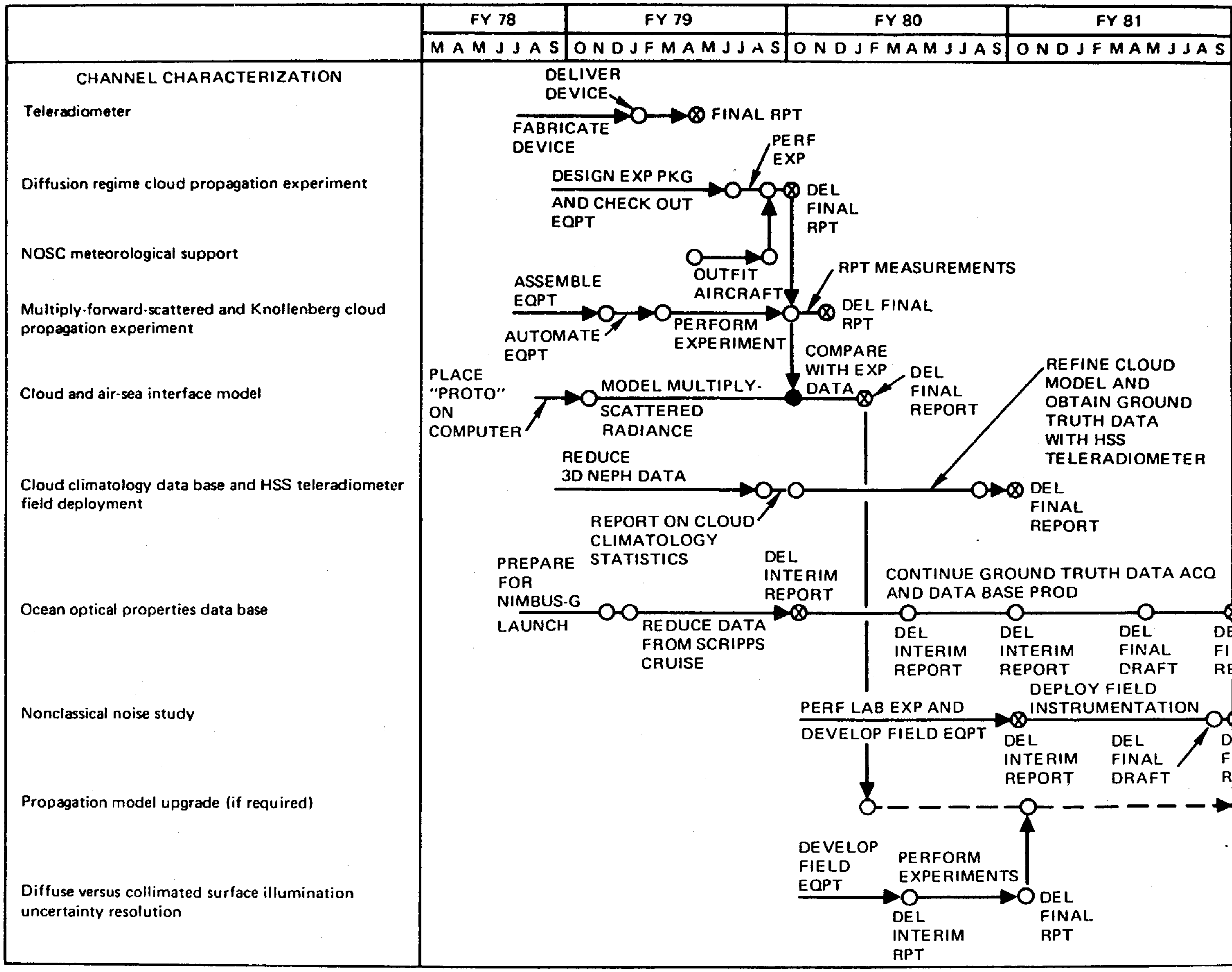

Figure 5. Channel characterization program schedule for strategic blue-green optical communications through FY 81.

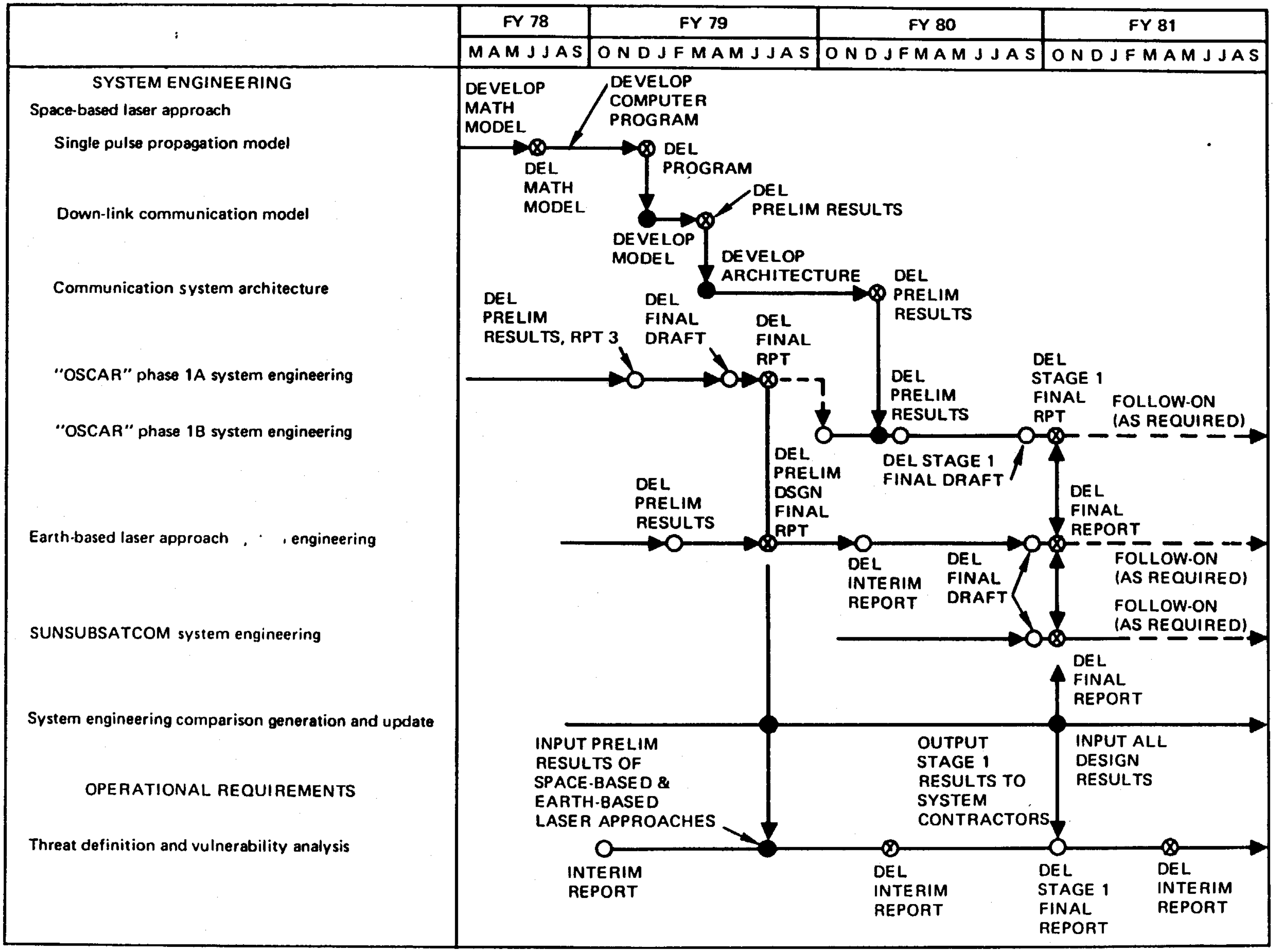

Figure 6. System engineering and operational requirements program schedule for strategic blue-green optical communications through FY 81.

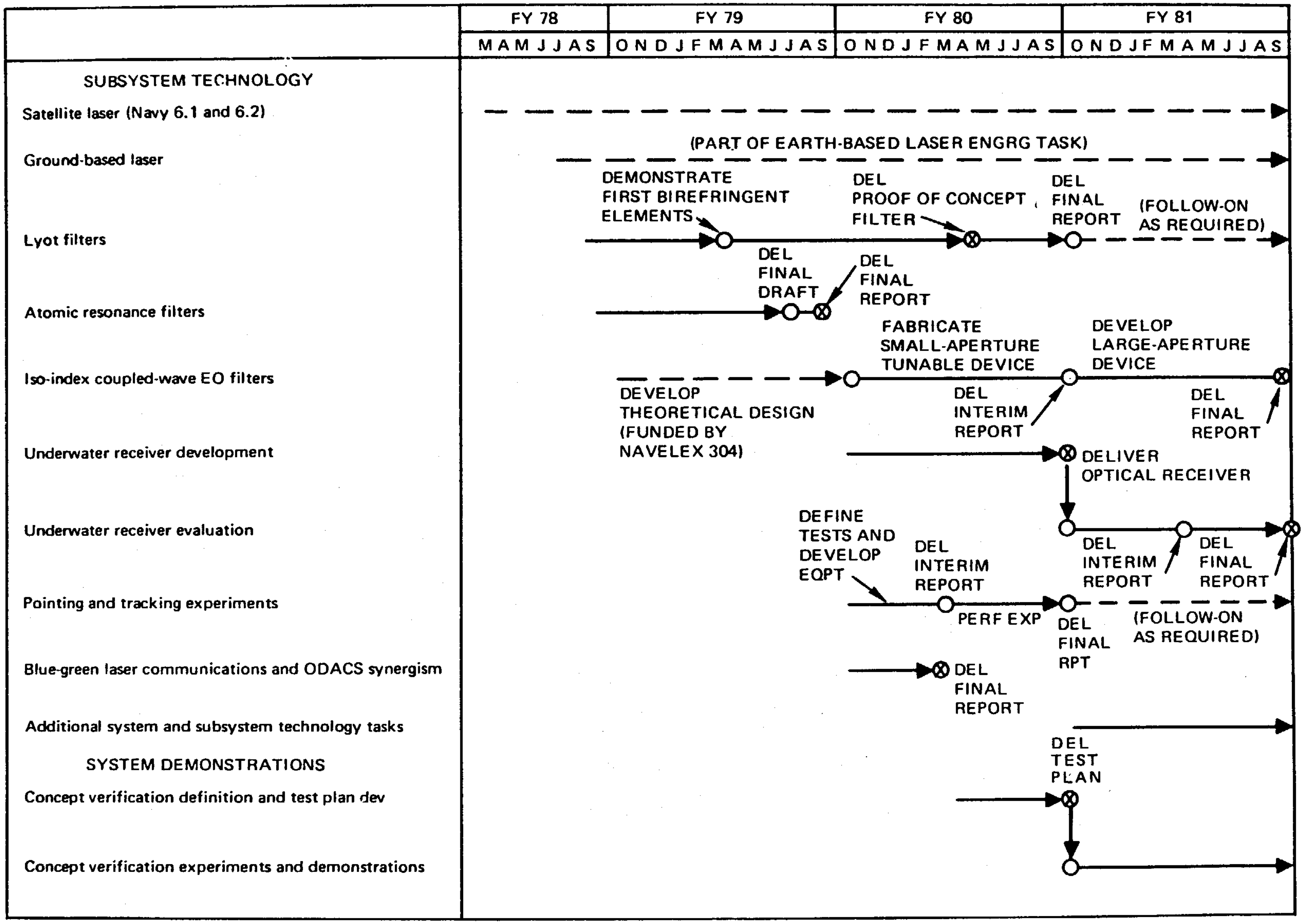

Figure 7. Subsystem technology and system demonstrations program schedule for strategic blue-green optical communications through FY 81.

REFERENCES

1. Optical Communications Between Underwater and Above Surface (Satellite) Terminals, by S Karp; IEEE Trans on Comm, COM-24, no 1, p 66–81.

2. NOSC Technical Document NELC TD 490, OPSATCOM Field Measurements, vol I and II, by R Driscol, F Martin, and S Karp, 1 June 1976.

3. NOSC TR 387, Naval Blue-Green Single-Pulse Downlink Propagation Model, by Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee, 1 January 1979.

APPENDIX A: BLUE-GREEN TRANSMISSION CHANNEL

The transport of optical energy through the atmosphere, clouds, the air-sea interface, and ocean water is of great concern to any system engineer tasked with designing a satellite-to-submarine optical communication link. These entities comprise the link's transmission channel; hence their analytic description must be as accurate and physically realistic as time, money and system margin will allow. The optical scatter channel is very complex. Fortunately, the fact that a satellite transmitter will produce semi-plane-wave illumination of the earth's surface greatly simplifies the analysis. Good, experimentally verified models now exist for describing propagation in sea water. Cloud propagation models, however, are not as accurate, partly because of the nature of the propagation medium itself. For sea water, the albedo of single scattering ranges between 0.25 and 0.6, with significant resultant absorption of multiply scattered rays that propagate extra path lengths. Thus the exponential irradiance dependence with depth is given approximately by the absorption coefficient plus a small correction. This correction is due to the additional path that the photons travel when they are multiply scattered, and it is albedo dependent. Likewise, multipath time spread is generally negligible because the long path rays are absorbed.

On the other hand, multiple scattering within a cloud is generally characterized by an albedo very close to 1, ie almost no absorption occurs in the clouds. Energy is merely redistributed, and losses observed at a receiver are attributed to light leaking out of the cloud. Since these multiple scattering effects are highly geometry dependent, the case of concern is primarily that of semi-plane-wave illumination of cloud tops. We have a great deal of natural experience in this case, since it relates to solar transmission through clouds. Even when optically thick clouds are present in the intervening path, the solar irradiance transmission is seldom below 0.01. In general, however, the characterization of the propagation effects of pulsed blue-green beams in a satellite-to-subsurface communications channel will be in terms of the time-dependent radiance measured at a distance below the scattering medium. Therefore, to fully understand the degradation of clouds in this channel, more than mere irradiance transmission needs to be known. Thus the technical uncertainties in clouds are primarily propagation "theory" related, whereas uncertainties in the water are due to a lack of quantification of parameters of the water mass (eg, absorption coefficient, scattering coefficient, mean square scattering angle, variations with depth, etc).

Of particular interest in characterizing the channel degradation effects of clouds are the following:

Characterization of total optical transmission and spatial spreading for finite beam diameters

Characterization of the propagation transition regimes: direct beam to multiple forward scatter to diffusive multiple scatter

Multipath time spread and geometrical time delays

Effects of inhomogeneous clouds and nonuniform boundaries

Characterization of side losses in clouds of finite lateral extent

Effects of Rayleigh scattering above the clouds, ie blue sky contributions

Angle of incidence behavior (very dependent on geometry and propagation regime)

Characterization of angular spreading of the energy exiting the cloud. (This will affect, for example, the air-sea interface coupling, etc.)

Fortunately, many of these channel degradation effects can be measured by using solar illumination for the prime geometry of interest. The sun provides a reasonable approximation to a point source (0.5°) and a good approximation to a semiinfinite plane wave. This enables one to measure simply most amplitude related propagation effects, such as total transmission, angle-of-incidence behavior, etc. The most difficult to characterize is the temporal and spreading behavior of the blue-green beam that excites the cloud.

Optimum communication system performance depends upon both the amount and form of the received signal. Under background-limited operation, for example, a small number of photons confined to a relatively short time span and a narrow angular spectrum is much more desirable than the same amount of light spread over a larger time interval and appearing to come from all directions. Thus, the quantification of multipath time spread, cloud transmittance, and angular spread, all incurred by an optical plane wave traversing an optical scatter channel, is of primary importance to the eventual realization of naval satellite-to-subsurface optical communications, the goal of the Strategic Blue-Green Optical Communications Program.

APPENDIX B: BLUE-GREEN LASER TECHNOLOGY REVIEW

Two Navy 6.2 system efforts are now driving the DoD development of blue-green laser technology: the Strategic Blue-Green Optical Communications Program, presently being funded jointly by NAVELEX, ONR, and DARPA, and the Ocean Detection and Categorization Technology Program presently being supported (in separate efforts) by NAVAIR and DARPA. These programs are singled out because they are projected to have similar future laser requirements in certain but not all respects and because the type of laser to be used by both probably will be ready for preliminary testing in FY 82. Furthermore, the particular laser requirements are significantly more difficult to achieve than the objectives of past efforts in this area. Therefore, a multi-year program was begun in FY 79 with the intent of developing such a laser. The laser development objectives are as follows:

Wavelength	480 ± 20 nm
Average output power	250 W
Pulse energy	0.5–5 J
Pulse repetition rate	50–500 pulses per second
Pulse width	50 ns
Efficiency	1%
Lifetime	10^8–10^{10} shots

It is presently felt that the best laser candidates for meeting the above performance specifications are frequency down-converted rare gas halide UV excimer lasers and in-band (490–502 nm) blue-green mercuric bromide lasers, recently developed by NOSC (ref B1). Although this appendix reviews all the potential optical sources considered, reference B1 explains why these two are considered the "best."

CURRENT CANDIDATES

Dye Lasers

Organic lasing dyes, commonly dissolved in an organic liquid, span the whole spectrum from the long ultraviolet to the near infrared. Most lasing dyes belong to several classes of which the better known are oxazine and cyanine. Most of the dyes lasing well in the blue-green belong to the flourinated coumarines. One of the main problems of dyes for military applications is their photochemical instability. A small fraction of the dye molecule excited by the pump light does not return to its ground state by flourescence but, instead, reacts with another constituent of the dye solution to form photochemical products. Usually these products are absorbed in the lasing region, thus the output goes down. To keep the concentration of the constantly forming product down, these laser systems must use large dye reservoirs, which add to the overall weight. Efforts that have been made to increase the stability of dyes by changing their structure have resulted in considerable improvement.

B1. Electro-optic Device Technology; PE 62762(N) XF62583091 FY 80 Block Program Plan, prepared by NOSC for N Butler, NAVELEX 304, June 1979.

In a combined NOSC-NWC program, the dye AC3F was found to be the best choice for flashlamp operation. Still, from small-scale laboratory tests, it was extrapolated that 1 litre of dye solution is necessary for an average laser power output of 1 watt over a period of 1 hour. Therefore, for a 10-watt laser to operate for 10 hours, 100 litres of dye solution would be required.

Several flashlamp types are used to pump dyes. They include linear lamps, coaxial lamps, and vortex-stabilized lamps. Linear lamps can be operated up to several hundred pulses per second, but the total number of shots is limited to a few million. Coaxial lamps work only at a few pulses per second with laser energies of up to one joule. Their total lifetime is also limited to about one million shots. In both of these lamp types, hot plasma in direct contact with the quartz walls erodes the walls. The combination of erosion and electrode sputtering limits the lifetime. This problem is avoided in the vortex-stabilized lamp, which is not permanently sealed with a fixed gas fill; instead the gas flows at high speed through the lamp. The resulting low-pressure region in the flow center stabilizes the hot arc, and the lamp walls stay cold. The gas flow also removes electrode sputtering from the lamp zone. With this arrangement, very long lamp lives have been observed and a lifetime of ten million shots seems to be achievable. A price has to be paid for this life improvement, however. The gas which gives highest pumping efficiency is zenon, which is much too expensive to be dumped at the output. This arrangement, then, requires gas recirculating equipment that includes pumps, compressor, heat exchanger, and filter. The increase in laser complexity, weight, and size is considerable. Still, design estimates indicate that a 10-watt average power (200 pps, 50 mJ) vortex-stabilized dye laser can be built to last for 10 hours with a total weight of about 350 pounds, including the dye reservoir. Development of all three flashlamp-pumped dye lasers has progressed far enough that brassboard models could be built for field experimentation. It is hoped that the laser will last longer than 10 hours and that only the dye would need replenishing.

Flashlamp-pumped dye lasers have pulse widths ranging from 0.4 to 1 μs. Proposals have been advanced to manipulate the laser pulse by optical means like slicing, varying the delay, then recombining. Although this method is sound in principle, the additional complexity and efficiency loss should make the short-pulse dye laser only a second choice. Therefore, the relatively long inherent pulse width would limit this laser to optical communication systems. The reduced SNR in background-limited operation caused by the increased counting period would have to be made up by an increased pulse energy. The overall efficiency of flashlamp-pumped dye lasers with spectrally narrowed output (1 nm) will be less than 0.5 percent. Order of magnitude increases are unlikely.

Laser-Pumped Dyes

The absorption bands of blue-green lasing dyes are located in the UV and can therefore be pumped efficiently with UV lasers. The newly developed excimer lasers, KrF (200 nm) and XeF (350 nm), which are especially useful for this purpose, will be discussed in detail later. Generally, the output pulse of the excimer lasers is short, about 20 ns, and the dye laser pulse follows the pump pulse. Furthermore, preliminary results indicate that the photochemical stability of dyes under this excitation is greater than that in flashlamp pumping. The efficiency of the excimer lasers is now only 2 percent, but improvements are expected. The conversion to dye output was observed to be about 15 percent efficient and is likely to be increased to 25 percent. Depending on the pump laser efficiency, 0.5 to 1 percent overall efficiency can be predicted. Presently, however, the development of excimer lasers is still in its early stages, and further efforts are needed to determine their practical potential.

Solid-State Lasers

Presently, the Nd^{3+}:YAG at 1060 nm is probably the most widely used pulsed laser in the military environment. In most applications, such as range finders and target designators, the required repetition rates are low and the pulse energies are moderate. The solid laser rod can be cooled only by surface conduction, which sets a limit to the average power obtainable from a crystal. To convert the 1060 nm output into the green, the frequency is doubled by second-harmonic generation (SHG) to a wavelength of 530 nm. To achieve short, energetic pulses, the laser rod has to be flashlamp-pumped and Q-switched. Commercially available are 532 nm Nd:YAG lasers with 50 pps and 150 mJ per pulse at a 20-ns pulse width. Several breadboard developments are sponsored by the Air Force to obtain 1 joule per pulse at 10 pps. Although frequency doubling and Q switching adds to the complexity of the system, solid-state lasers are quite reliable if they are well designed. Flashlamp life is on the order of 10 million shots. The longer life compared to dye flashlamps is based on the fact that Nd^{3+} ions in a solid host have a flourescence lifetime about 10^5 longer than dye molecules. The long flourescence lifetime allows for relatively long pulse operation of the flashlamp, with slow rise times and low current densities.

The wavelength of doubled Nd:YAG is unfortunately too long, which is an important factor for systems trying to go to great depth. At a depth of 300 metres, for instance, almost 1000 times the pulse energy is needed to achieve the same power flux at 532 nm as at 480 nm.

Total efficiencies of doubled YAG lasers are not considerably better than flashlamp-pumped dye lasers. Although the long-pulse operation of the fundamental at 1064 nm can be 1 percent efficient or better, by the time Q switching and SHG is thrown in, efficiencies are only 0.2 percent at best.

Nevertheless, because it is free from circulating gases or liquids, the solid-state laser does have special appeal for space application. Under the 405B Program, the Air Force developed a 0.2 W cw pumped, mode-locked 532 nm Nd:YAG laser that is close to being space-qualified. For Navy applications, however, the wavelength, mode of operation, and output level would have to be different.

Under normal operating conditions, Nd:YAG lasers at 1064 nm are of the $^4F_{3/2} \rightarrow {}^4I_{11/12}$ transition, which has the lowest threshold. By cooling the rod to −40°C and spoiling the gain at 1064 nm, another line at 946 nm belonging to the group of $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition can be made to lase. When frequency-doubled, this line is located within the transmission window of clear ocean water. Appreciable power levels, however, could not be estimated at 946 nm because the unavoidable temperature increase connected with higher power changes the output in favor of the 1064 nm line. It is very doubtful that a practical laser at 946 nm (and consequently 473 nm) could be developed that uses Nd:YAG. There are, however, different crystal hosts into which Nd^{3+} can be doped. The Nd^{3+} is then exposed to a different crystal electric field, affecting somewhat its energy-level splitting as well as the branching ratio of the different transitions. One host in particular – CAMGAR (Ca 1/2 $Mp_2Ge_3O_{12}$) – favors the shorter wavelength transition. Very recently, Nd:CAMGAR was made to lase at room temperature at the 946 nm line with argon-ion laser pumping.

In addition to Nd in different hosts, Ho^{3+} ion in $HoLiF_4$ crystals has lased at 970 nm. The required temperature was about −200°C. Also Pr:YLF was lased recently at room temperature at 479 nm when pumped with a wavelength-tuned dye laser.

It is unlikely that any of these solid-state lasers using either different hosts or different ions will exceed the efficiency of Nd:YAG. At best 0.1 percent total efficiency can be expected ultimately with an average power output of several watts in the blue-green. However, since the advantages of going to the optimum wavelength are great and there is a paucity of laser candidates for space-based applications, exploratory investigations are pursued on a limited scale.

Copper Lasers

Among the several proposed and investigated candidates for cyclic, self-transitioning lasers, the copper laser is the only one which has achieved significance. This is probably explainable by the unique energy level spacings in the copper atom and the favorable ratios of transition probabilities.

The natural Cu atom lases at two wavelengths simultaneously: 510.6 nm (green) and 578.2 nm (yellow). The ratio of green-to-yellow output energy is about 2:1. Note that when copper laser outputs are quoted, it generally means the total output. Obviously, for any Navy blue-green system application, only the 510.6 nm line is of importance.

Since copper metal has a negligible vapor pressure at room temperature, a temperature of about 1500°C is required to increase the copper atom density to a lasing level. The most efficient way to generate and maintain that temperature is to use the discharge heat itself. Depending on the power level and heat shield design, the discharge tube, which is filled with inert buffer gas and copper metal, is pulsed for 25–30 minutes before lasing occurs. To maintain an even temperature, a high repetition rate is normally required. In present designs, 6 kHz is optimum and 1 kHz seems marginal. Best achieved performance values to date are 6 kHz, 15 W (total) output with 1 percent efficiency and 1 kHz, 12 W (total) at 0.5 percent efficiency. The highest output energy achieved so far at 510.6 nm is 8 mJ per pulse. Scaling to higher pulse energy has been investigated but was not successful. At higher discharge volumes and/or vapor pressures, losses caused by discharge instabilities and superradiance become severe.

At the present stage of development, copper vapor migration to the window areas limits the total lifetime of a laser tube to 10–30 hours. To achieve hermetic seals at 1500°C is difficult; therefore a small flow of buffer gas is maintained. This requires constant pumping of the laser tube by a vacuum system. Further work in these areas is being supported by DOE and the AF, and chances are good that sealed-off operation for tens of hours will be achieved. The copper laser might then be a compact system, delivering several kHz of short pulses (10–20 ns) with about 10 mJ of energy at 510.6 nm and with 1 percent overall efficiency.

In an attempt to avoid the high temperatures necessary for metallic copper lasers, copper compounds with sufficient vapor pressures at lower temperatures have been investigated. The only useful class of compounds found to date are the copper halides, operative between 500° and 600°C. At high PRFs, each electrical discharge pulse disassociates some of the halide molecules into copper atoms and halogens and simultaneously excites the copper atoms left from the previous pulse. So far, the copper halide lasers have demonstrated pulse energies only up to 1 mJ in a repetitive pulsed mode. With the buffer gas flowing, efficiencies between 0.5 and 1 percent have been reported. In sealed-off operation, with tubes lasting several hundred hours, efficiencies were between only 0.1 and 0.3 percent.

An optimum pulse repetition rate for halide lasers seems to be around 15 kHz. The lower efficiency in sealed-off tubes is presently not understood. Efforts to scale the copper halide to higher pulse energies have so far been unsuccessful. As in the case of metallic copper lasers, discharge instabilities and superradiance losses seem to limit the achievable pulse energy. Probably because of the electropositive halogen atoms, this limit is an order of magnitude lower than in the metallic copper laser.

The sealed-off copper halide laser could be developed into a fieldable device delivering several watts of average power at 510.6 nm with a PRF of 10 kHz and an overall efficiency of 0.3 percent. With further support, the operating life could be extended from the present few hundred hours to about 1000 hours.

Excimer Lasers

An excimer is a usually diatomic molecule that has a stable excited electronic state but an unstable ground state. The more important excimers for lasing belong to a class formed by the inert gasses and halogens – in particular ArF, lasing at 193 nm; KrF, at 250 nm; and XeF, at 350 nm. All three lasers are in the UV, their output has to be frequency down-converted into the blue-green. Very high pulse energies have been obtained, particularly with KrF, by using e-beam excitation (several hundred joules per pulse) at essentially single-shot operation. Electrical discharges sustained with smaller electron beams can work at several pulse rates. But for applications in Navy systems requiring both higher repetition rates and small size and weight, direct electrical discharge without electron beams seems to be of greatest potential.

In a typical KrF laser, for example, He is mixed with a few tenths of a percent of F_2 and several percent of Kr; after photo preionization, the gas mixture is exposed to a fast electrical discharge. By this means pulse energies of several hundred mJ can be achieved with an efficiency of 1 percent. The pulses are typically 20 ns long.

This type of UV excimer laser probably can be developed for incorporation into devices delivering short pulses of several joules at repetition rates of hundreds of pulses per second. The UV output efficiency is presently expected to reach 3–5 percent. With a down-converter like a dye, output levels on the order of a joule at total overall efficiencies close to 1 percent could be then expected.

Several problems must be overcome before this type of performance can be realized. For one example, efficiency increase of the UV output must be accomplished by (a) detailed study of the discharge kinetics for the purpose of slowing and hopefully eliminating any efficiency bottlenecking and (b) improved methods of coupling the electrical energy stored in the driver into the lasing plasma. For another, fluorine is a very reactive gas; and although many components in the excimer laser get tarnished by surface fluorination, some irreversible processes keep going. For the output levels required, the gas mixture will have to flow at considerable speed through the laser cavity to carry away the generated heat. The corrosiveness and toxicity of F_2 and the high price of Xe and Kr make it absolutely necessary for the mixture to be recirculated in a closed system. Every component in the total system must be compatible with F_2. Fabrication with such components is thought not impossible to achieve, but it will require considerable development.

Next to the infrared molecular lasers, UV excimer lasers have exhibited the highest laser efficiency to date. In particular, KrF at 250 nm has been operated at high pulse energies (> 100 J) and high efficiencies (~ 5% deposited energy efficiency), by using e-beam excitation. More recently, XeCl at 308 nm has been shown to perform with similar efficiencies (ref B2, B3). For the purposes of interest here, the advantages of XeCl over KrF are twofold: 308 nm is closer to the blue-green spectral region and the down-conversion losses are therefore lower; and chlorine is considerably less chemically active than fluorine, which makes the prospect of achieving long-lived, closed operation much more realistic. Direct e-beam excitation, however, is not likely to be compatible with long-term operation: the required current densities (10–20 A/cm^2 peak) constitute such a load on both the cathode and the foil of the electron gun that, at least at this date, long-term operation cannot be predicted. UV excimer lasers, including XeCl, have also been operated by UV-preionized discharge and e-beam sustained discharge. Both methods now have about 1% efficiency, and efforts are underway to increase this number to 2–3%.

Down-conversion of the XeCl 308 nm output into the blue-green can be achieved in several ways. Particularly interesting because of their high efficiency and photochemical stability (as compared to organic dyes) are stimulated Raman scattering processes. With molecular gases (H_2, D_2), at least three consecutive steps are required to arrive in the 480 nm region. With metal vapors, however, only one step is needed. Burnham and Djeu (ref B4, B5) recently were able to demonstrate 50% photon or 34% energy-conversion efficiency by using lead vapor in a heat pipe oven 100 mm long. Figure B1 shows the energy levels involved in this electronic stimulated Raman scattering process.

The incoming pump photon ν_p (32 467 cm^{-1}) gives off 10 650 cm^{-1} of its energy to the lead vapor and emerges as a photon of ν_R = 21 817 cm^{-1}, or λ_R = 458 nm. With a longer interaction path, almost unity quantum efficiency – about 65% energy conversion efficiency – probably can be obtained.

NEW POTENTIALS

Several novel blue-green laser candidates are discussed in the following paragraphs. Some of them have already lased but are still in an early research stage, so that their eventual practicality cannot be accurately assessed. Others are mere concepts which still await experimental demonstration.

Helium-Nitrogen Change Transfer Laser

At pressures above a few atmospheres, a mixture of He and N_2 can be excited to lase by either an e-beam or an electrical discharge. Ionized He molecules transfer their charge to N_2, and it is the N_2 that lases on three vibrational levels of the $B^2\Sigma_u^+ \rightarrow X^2\Sigma_u^+$ transition. The vibrational levels involved are (0,0) at 391.4 nm, (0,1) at 427.8 nm, and (0,2) at 470.9 nm. The last line is of particular interest because it is close to the maximum ocean transmission and would not need an additional down-conversion. A further advantage of this laser over the rare-gas fluoride laser is that the gas mixture is completely noncorrosive. Also

B2. Efficient Operation of the Electron-Beam Pumped XeCl Laser, by LF Champagne, Appl Phys Lett, September 1978 (in press).

B3. Efficient e-Beam Excitation of XeCl, by DE Rothe, JB West, and ML Bhaumik, IEEE J Quant Electr, in press.

B4. Paper X.7, by R Burnham, at 10th Intern Quantum Electronics Conf, Atlanta GA, 29 May–1 June 1978.

B5. R Burnham and J Djeu, to be published.

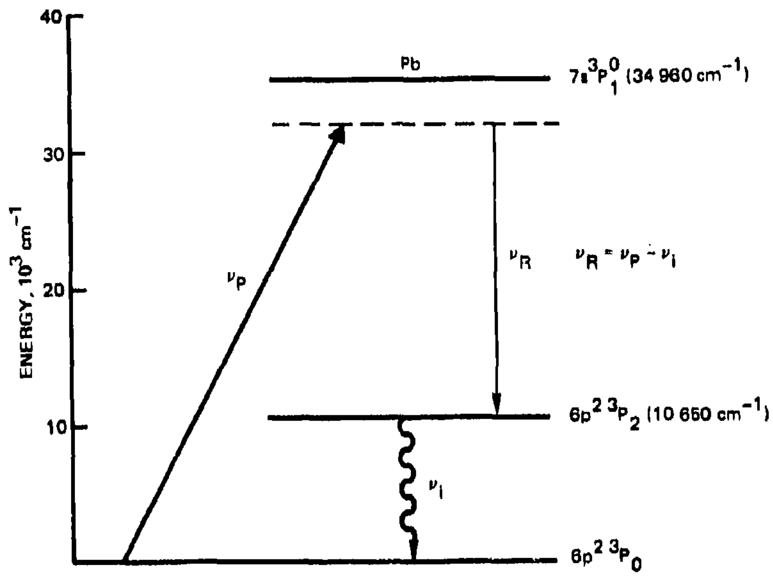

Figure B1. Stimulated Raman scattering in lead vapor.

the output pulses are short. Yet to be proven, however, is whether it has reasonable efficiency at practical pressures. ONR-sponsored work toward that end is being performed at the University of Texas at Dallas.

Diatomic Sulfur Laser

S_2 at 500°C has recently been reported to lase at many lines between the blue and red spectral region when optically pumped by a tunable frequency-doubled dye laser. The lasing wavelengths belong to different vibrational-mechanical levels of the $B^3\Sigma u \rightarrow X^3\Sigma u$ transition, depending on the excitation wavelength. Weak lasing was also observed when S_2 is pumped with an N_2 laser. The pump lasers, either N_2 or frequency-doubled dye, are inefficient. Their inefficiency, coupled with the inefficiency of the conversion process, makes the optically pumped S_2 laser impractical. The possibility exists, however, that S_2 would lase by direct electrical discharge and, it would be hoped, in the blue-green. Work directed toward that goal is proceeding at several laboratories.

Solid-State Down-Conversion

Another scheme proposed for down-converting UV excimer radiation is to pump solid-state laser rods. It is possible that one or several combinations within the multitude of energy-level combinations available from rare-earth ions in different crystal hosts would have the correct separation for absorption in the UV and emission in the blue-green. So far, no experimental proof has been forwarded. A point in favor of solid-state down-converters is their apparent stability: they exhibit no elevated temperatures as in vapor and no photodecomposition as in liquid dye solutions. But whether the solid materials will be immune to color center formation when exposed to the intense pump radiation is still open to question.

"In-Band" Excimer Lasers

PROPOSED MATERIAL COMBINATIONS. Things would be much simpler if efficient excimer-type lasers were available that lase directly in the blue-green region (in band). Several material combinations have been proposed, among them HgCd, HgTl, and TlXe. These are all predicted to lase in the blue-green, but experimental verification is still lacking.

MERCURIC BROMIDE DISSOCIATION LASER. Another development worth mentioning in this context is the direct-discharge excitation of mercuric bromide. Dissociative excitation of $HgBr_2$ was first demonstrated by the method of photodissociation with an ArF laser as pump (ref B5, B6). More recently, dissociative excitation by electron impact in an electric discharge was successful (ref B7–B9). In a typical experiment, a transverse discharge cell is filled with 700-torr Ne, 100-torr N_2, and 2-torr $HgBr_2$ vapor (temperature $\sim 150°C$). After UV preionization, the main discharge pulse of 100 joules stored energy results in a 20-mJ output pulse of 40 ns width. Calculating the energy deposited in the plasma from voltage and current waveforms across the discharge gap gives a deposited energy efficiency of 1%. The extracted energy-to-volume ratio is close to 1 mJ/cm^3. It is expected that with a better understanding of the excitation/laser kinetics and an improved impedance matching of the driver and plasma, an overall efficiency of 0.5% or possibly even 1% can be approached. The output wavelength of the HgBr laser has been wavelength-tuned, with the aid of a grating, from 505 to 489 nm.

Output pulse energy scaling to the joule levels should be feasible. In many aspects this type of laser is similar in behavior to the UV rare-gas halide excimer lasers, from which the desired performance is already realizable. A schematic energy diagram of the excitation and lasing process is shown in figure B2. Note that in both excitation methods, the parent molecule, $HgBr_2$, recombines after dissociation.

B6. Mercuric Bromide Photodissociation Laser, by EJ Schimitschek, JE Celto, and JA Trias, Appl Phys Lett, vol 31, p 608, 1977.

B7. Mercuric Bromide Dissociation Laser in an Electric Discharge, by EJ Schimitschek and JE Celto, Opt Lett, vol 2, p 64, 1978.

B8. Paper H.6, by EJ Schimitschek and JE Celto, at 10th Intern Quantum Electronics Conf, Atlanta GA, 29 May–1 June 1978.

B9. Discharge Pumped Mercuric Halide Dissociation Lasers, by R Burnham, Appl Phys Lett, vol 33, p 156, 1978.

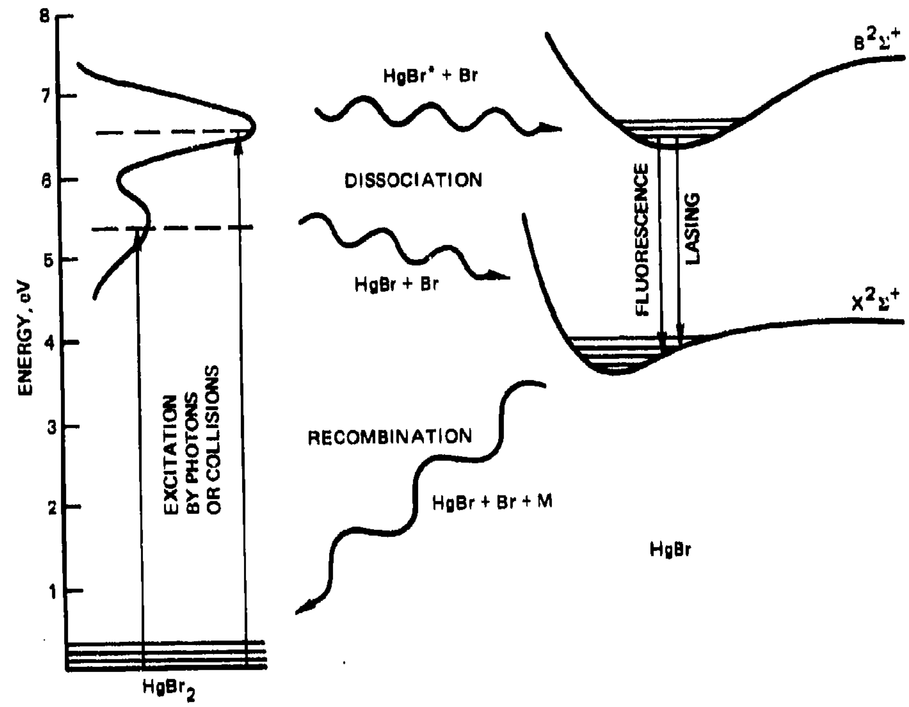

Figure B2. Dissociative excitation of $HgBr_2$/HgBr (schematic).

APPENDIX C: BLUE-GREEN OPTICAL FILTER TECHNOLOGY REVIEW

Background rejection in an optical communication system during daytime operation is a serious problem, especially for an underwater receiver located at substantial depths. Here the photons in the down-dwelling signal beam have lost much of their original directionality through multiple scattering processes in the water. Signal strength is lost unless the FOV of the receiver is opened to subtend this spre... ng. The total solid receiver FOV might have to be as large as one steradian, or 32°. On the other hand, the spectral passband of the receiver should be narrow enough to pass essentially only photons that are within the signal line width. A narrow passband filter has to be part of the receiver.

The simultaneous achievement of wide FOV, narrow spectral passband, good transmission, and sufficient aperture size is a nontrivial problem.

It can easily be shown that the SNR bears the following relationship to those factors:

$$SNR \sim \frac{A_{eff} \cdot T \cdot \theta_F^2}{\Delta\lambda_F} , \qquad (\Delta\lambda_F > \Delta\lambda_L ; \theta_F < \theta_B)$$

where

A_{eff} = effective receiver aperture, which might or might not be equal to the optical filter aperture

T = filter transmission at the center wavelength

θ_F = linear receiver FOV half angle

$\Delta\lambda_F$ = spectral width of the filter

$\Delta\lambda_L$ = spectral width of the transmitted signal

θ_B = linear signal-spread half angle at the receiver

In developing the optical filter portion of the FY 80–81 investment strategy of the Strategic Blue-Green Optical Communications Program Plan, several potential large-aperture, wide-FOV, narrow spectral passband filter concepts were considered. The intent of this appendix is to describe the blue-green optical filter technologies investigated.

INTERFERENCE FILTERS

The most commonly used narrow-band filter today is the multistack dielectric interference filter. For example, spectral width of 1 nm and transmission of 50% constitute the present state of the art. Discs up to 6 inches in diameter can be fabricated, and these can then be assembled in arrays to form much larger sizes. The main shortcoming of this filter type is a strong λ-dependence of the passband with angle of incidence:

$$\Delta\lambda_F = \lambda_L \sqrt{1 - \frac{\theta_F^2}{n_{eff}^2}} ,$$

where λ_L is the design wavelength center measured at the normal and n_{eff} is the effective index of refraction of the dielectric stack, between 1.6 and 1.8. To stay within a transmission band of, for example, 1 nm, the angles of incidence have to be restricted to just a few degrees. To achieve a large FOV, the signal beam has to be "straightened out" by optical means before it passes the filter. This requires a filter plane many times the size of the effective aperture (fig C1).

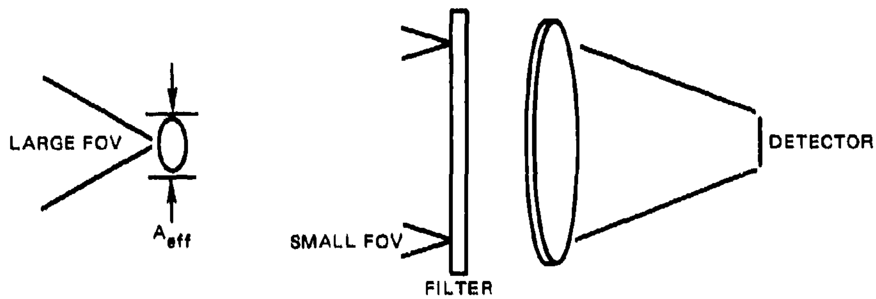

Figure C1. Relations between entrance aperture and field of view.

Improvements in interference filter technology can come only from better dielectric materials that yield higher transmission at lower angle sensitivity (higher n_{eff}). For an aircraft receiver, which needs an FOV of only about 1°, interference filters seem adequate.

BIREFRINGENT FILTERS

There may be significant advantages in using birefringent filters rather than interference filters of the Michelson and Fabry-Perot type. An advanced filter based upon birefringence-induced interference is the Lyot filter (fig C2). It consists of an entrance polarizer, a birefringent plate, and an exit polarizer. The purpose of the entrance polarizer is to prepare a single state of polarization, because interference does not occur with light originating from different polarization states. The birefringent plate has its optic axis in the plane of the plate and at 45° to the polarizer axes. Waves propagating through the plate may be resolved into components parallel and orthogonal to the optic axis. Those polarized along the axis propagate at velocity c/n_o; those perpendicular, at velocity c/n_e, where n_o and n_e are the ordinary and extraordinary indices of refraction of the birefringent material. Since the entrance polarizer is at 45° to the optic axis, equal amounts of light are in the components parallel and perpendicular to the optic axis. After propagating along the length of the birefringent plate, the two polarized beams are, in general, out of phase. The exit polarizer, parallel to the entrance polarizer, passes equal components of the two beams. Since the two beams arose from the same state, and since they have incurred a phase difference between them, they can interfere similarly to the two beams of a Michelson interferometer.

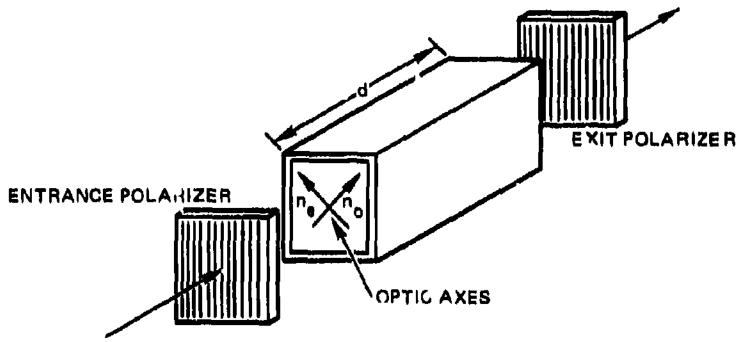

Figure C2. Lyot filter.

The advantage of the Lyot design, however, arises from the off-axis propagation characteristics of birefringent materials. Parallel and orthogonal to the optic axis, the respective angle sensitivities are as follows:

$$\left.\frac{\Delta\lambda}{\lambda}\right\|_{\parallel} = -\frac{\sin^2 i}{2n_o^2}$$

and

$$\left.\frac{\Delta\lambda}{\lambda}\right\|_{\perp} = +\frac{\sin^2 i}{2n_e n_o} ,$$

where i is the angle of incidence at the crystal face. Along the optic axis the angular sensitivity is the same as a Michelson; but orthogonal to the axis, the difference in curvature between the ordinary and extraordinary waves reverses the ordinary angular sensitivity.

The difference in the sign of angular sensitivity in orthogonal directions is the physical phenomenon that allows construction of a system of much lower angular sensitivity. The Lyot wide-field element is constructed by splitting a normal element in half and rotating the parts so that their optic axes are orthogonal. In addition, a half-wave plate is inserted between the halves, with its axis along the bisector of the angle between the optic axes. Finally, the filter element is inserted into a telecentric optical system designed to further enhance its angular performance.

Analysis indicates that with improved materials, wide-angle, narrow-band filters with reasonable aperture and transmission could be built. For instance, filters with $\Delta\lambda = 0.1$ nm, $i = 65°$ (FOV = 130°), effective aperture $\geq$ 100 mm and T closely approaching 50% might be achievable. This approach, while complex, presently appears more promising than others. It also has the advantage of being tunable, which is probably a necessary feature if the laser wavelength is fixed.

ABSORPTION-TYPE FILTERS

Ideally these would not be dependent on the angle of incidence. The problem is to find materials with very narrow transmission lines at selectable blue-green wavelengths and with high optical density elsewhere. By combining either sharp cutoff semiconductors and photoconductors or rare-earth ion and organic dye solutions, normally bandwidths of only 5 to 10 nm can be achieved. Very recently, work on graded semiconductors (II–VI compounds) was reported in which a 1 nm bandwidth was achieved. By changing the composition of the components, the transmission peak can be shifted. At this stage of development the eventual usefulness of this approach is difficult to predict.

RESONANCE-TYPE FILTERS

Resonance absorption and resonance reflection in atomic or molecular vapor have been investigated for narrow-band filtering. The main shortcoming of this approach for Navy applications is the extreme scarcity of materials with suitable transitions in the blue-green region. Since the transitions are fixed, the laser would have to be tuned to match the transition. The line widths in vapor transitions are normally very narrow (10^{-3} nm). Dye lasers are the only ones now truly tunable in the blue-green. Although dye lasers have been spectrally narrowed to about 10^{-4} nm for specific experiments, their overall efficiency drops drastically. To keep the efficiency at a reasonable level, spectral narrowing only to 1 nm – or at the very best, 0.1 nm – might be realistic. Another problem with resonance absorption is the inefficiency that accompanies collecting of the isotropically reradiated fluorescence. At present, this approach does not look very promising.

ACOUSTO-OPTICAL FILTERS

These filters actually belong to the interference class of filters except that the periodic structure is caused by acoustic waves in a single crystal. Thus their filtering action is also dependent on the angle of incidence. Their main advantage is that they can be rapidly tuned by changing the electric driver frequency that generates the acoustic waves. As in the case of multistack dielectric interference filters, optical means would have to be employed to reduce the divergence angle of the incoming signal beam. Thus the filter must be much larger than the effective aperture. So far, the crystals used for acousto-optical filters, such as $CaWO_4$, are available only in small sizes. But even if larger crystals were available, it might be difficult to establish standing acoustic waves uniformly over their entire area. This approach should be much more useful when very rapid tuning is required.

ISOINDEX COUPLED-WAVE ELECTRO-OPTIC FILTER

A new optical filter concept that surfaced recently after having been first proposed over a decade ago is based on the accidental isotropy in refractive index of certain uniaxial semiconductors that occurs near the band edge. Light energy can be coupled between ordinary and extraordinary polarizations at the isotropic point by an applied dc electric field. When placed between crossed polarizers, these materials can thus act as narrow-band filters. The field-of-view characteristics have been analyzed, and it is concluded that this type of filter can, in principle, accommodate a 2π field with less than 20% increase in passband over that of the narrow-field condition. It is noted, in particular, that $AgGaS_2$ exhibits the required change of sign of its birefringence at the desirable wavelength of 497 nm (blue-green), with a rate of change that would provide a passband of only 0.01 nm in a 20-mm sample.

DISPERSIVE REFLECTION FILTER

With the dispersive reflection filter, the dispersive properties of resonant absorption that have been used in the infrared to create narrow-band reflectors at Restrahlen frequencies are extended into the blue-green portion of the spectrum. In the presence of strong resonant absorption, the dielectric constant of a medium can actually go negative over a narrow wavelength range, and this leads to a material which is highly reflective only over this small wavelength range. This process is not angularly selective, and it can achieve narrow line widths through multiple reflections. The materials considered to date which have resonances in the blue-green portion of the spectrum include rare-earth salts, transitional metal ions and dye crystals. Each material has its own particular disadvantage for this application; until recently, operation at liquid He temperature appeared to be necessary for this approach. Recently it has become apparent that a hybrid solution to the problem may well lead to a room-temperature narrow-band filter. The hybrid approach will avoid the necessity of finding an atom which simultaneously has a high oscillator strength and narrow line width. Very narrow line widths appear achievable at room temperature by (1) selecting an atom such as a divalent rare earth with high oscillator strength but insufficiently narrow line width (to reduce the dielectric constant) and (2) adding to the same host an atom with lower oscillator strength and sufficiently narrow line width, such as a trivalent rare earth (to cause the dielectric constant to go negative). Such effects have been observed at 340 nm with Er^{2+}:Er^{3+}. A specific example for blue-green room-temperature operation is Sm^{2+}:Pr^{3+}.

DEGENERATE FOUR-WAVE MIXING

The filter concept that offers the best potential performance is based on degenerate four-wave mixing. In principle, line widths narrower than 0.01 nm, full 2π-steradian FOV, and signal amplification can simultaneously be achieved. This area, however, is the least mature, and additional work is required. One area of great importance is the scattering of the pump lasers onto the detector by the interaction medium. Preliminary calculation of such background noise has been made, and it appears possible to obtain quantum-noise-limited performance.